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Review

Advances in ingredient and processing systems for meat and meat products

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ABSTRACT

Changes in consumer demand of meat products as well as increased global competition are causing an unprecedented spur in processing and ingredient system developments within the meat manufacturing sector. Consumers demand healthier meat products that are low in salt, fat, cholesterol, nitrites and calories in general and contain in addition health-promoting bioactive components such as for example carotenoids, unsaturated fatty acids, sterols, and fibers. On the other hand, consumers expect these novel meat products with altered formulations to taste, look and smell the same way as their traditionally formulated and processed counterparts. At the same time, competition is forcing the meat processing industry to use the increasingly expensive raw material "meat" more efficiently and produce products at lower costs. With these changes in mind, this article presents a review of novel ingredient systems and processing approaches that are emerging to create high quality, affordable meat products not only in batch mode but also in large-scale continuous processes. Fat replacers, fat profile modification and cholesterol reduction techniques, new texture modifiers and alternative antioxidant and antimicrobial systems are being discussed. Modern processing equipment to establish continuously operating product manufacturing lines and that allow new meat product structures to be created and novel ingredients to be effectively utilized including vacuum fillers, grinders and fine dispersers, and slicers is reviewed in the context of structure creation in meat products. Finally, trends in future developments of ingredient and processing systems for meat products are highlighted.

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1. Introduction

Changing consumer demands and increasing global competition are causing the meat product manufacturing sector to embrace new processing technologies and new ingredient systems, which is remarkable if one considers the historically traditional and long term approach to product and process development in the meat industry. This is likely because the long standing positive consumer perception that meat and meat products are very good sources of minerals, vitamins, and contain "complete" proteins (i.e. proteins that in contrast to many plant-based proteins contain all nine of the essential amino acids) is gradually giving way to a more negative view (Verbeke, Pérez-Cueto, de Barcellos, Krystallis, & Grunert, 2010). Meat and meat product consumption is gradually being seen as causes for increased risks of attracting chronic diseases such as obesity, cancer and stroke. This is particularly the case in the United States, where incidences of obesity, cardiovascular disease, hypertension and cancer are increasing thereby putting an increasing burden on health care systems (CDC National Center for Chronic Disease Prevention, 2005).

While this view often neglects that meat is also an essential factor in maintaining human health, it nevertheless forces the meat and meat product industry to react. This change is by no means just affecting the meat processing industry. A similar process has been and continues to take place within the entire food manufacturing sector. This has led to the food industry paying an increased attention to the relationship between food consumption and human health and wellness. Consequently, a new class of foods, the so-called "functional foods" are being developed that either contain components that have beneficial physiological effects or that are void of components that depending on intake amounts may negatively impact consumers health. This approach has been strengthened by an increasing number of clinical research studies that have demonstrated tangible health benefits that may be derived from intake of bioactive compounds as part of consumers' daily diet. In Europe, these new food products have been labeled "novel" foods and food ingredients and by definition contain food ingredients that have not been used for human consumption to a significant degree (The European Parliament and the Council of the European Union, 1997).

The manufacturing, storage and distribution of functional or novel foods that contain bioactive food components pose significant challenges to the food industry as a whole, and by virtue of its portfolio of traditional products to the meat product manufacturing sector in particular. The Foundation for Innovation in Medicine in 1991 defined bioactives as "… any substance that may be considered a food or part of a food and provides medical or health benefits, including the prevention and treatment of disease" (IFIC, 2006). Bioactive compounds have shown to exhibit physiological beneficial effects upon ingestion (Ellinger, Ellinger, & Stehle, 2006; Harris & Bulchandani, 2006; Ratnam, Ankola, Bhardwaj, Sahana, & Kumar, 2006; Schwalfenberg, 2006; Theobald, 2006). Most bioactives are naturally occurring compounds and can be extracted from plant and animal sources thereby adding value to the commodities from which they have been derived. Examples of prominent bioactive compounds include phytosterols which may help to prevent the accumulation of cholesterol (Nissinen, Gylling, & Miettinen, 2006; Polagruto et al., 2006; Rasmussen et al., 2006), lutein which retards macular degeneration (Moeller, Jacques, & Blumberg, 2000; Trevithick et al., 2005) and ω-3 fatty acids (Harris & Bulchandani, 2006; Jabbar & Saldeen, 2006; Rose & Holub, 2006; Schwalfenberg, 2006; Zeman et al., 2006). For ω-3 fatty acids in particular, multiple large-scale population (epidemiologic) studies and randomized controlled trials of intake of recommended amounts of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) from fish oil have shown to lower triglycerides, reduce the risk of death, heart attack, dangerous abnormal heart rhythms, and strokes in people with known cardiovascular disease. Interestingly, while not aggressively marketed yet, most meat products contain inherently a potent bioactive compound; namely conjugated linoleic acid (CLA) at approximately 3–8 mg of CLA per gram of fat. In addition to its anticarcinogenic property, CLA has antioxidative and immunomodulative properties and appears to play a role in bone metabolism as well as diabetes and obesity risk control.

A prerequisite for physiological action of many bioactives is that (a) sufficient quantities of components are present in the food systems (b) that the compounds remain physically and chemically stable throughout production, storage and consumption (Schmidl & Labuza, 2000) and (c) upon consumption pass through the human digestive system in a physical form that allows the compounds to be optimally absorbed in the intestinal tract. Ideally, the bioavailability, that is the fraction of the administered bioactive compound that reaches the systemic circulation, should be as high as possible. However to date, the bioavailability of many compounds once incorporated in a food matrix is extremely low. This is because the compounds may not be stable during processing and/or the compounds may physically and chemically interact with the multi-component, multiphase food. In this respect, meat products are particularly complex because of their high content of proteins, lipids, and minerals that may lead to a multitude of physical interactions and chemical reactions that cause changes in flavor, taste and appearance thereby potentially reducing consumer acceptance of functional meat products.

A consequence of the above mentioned changes is an increasing trend towards the manufacturing of "classical" meat products with altered formulations. For example, heated or fermented, emulsified and non-emulsified sausages are manufactured with less fat, less salt, less nitrite, and even less meat (using non-meat based proteins or hydrocolloids as substitutes). Unfortunately, the removal of these compounds causes a multitude of mostly undesirable changes (lower microbial stability, lower sensory acceptance, and lower water holding capacity) that are often difficult to compensate. Similarly, addition of for example polyphenolic components while physiologically beneficial may impact the formation of a stable protein network in the meat product and often induces astringent flavors, both of which are highly undesirable changes. The emerging gap in the knowledge base has resulted in a renewed research activity in the meat sciences to establish a scientific basis for the rational design and manufacturing of meat products that contain non-traditional ingredients. This review article is intended to give the reader an overview over developments in this area. By nature, this review is a snapshot of the current state of the science and is not meant to be completely comprehensive. Rather, the article intends through case studies of ingredient and processing systems to show the direction in which the science is developing. The literature cites extensive reviews that readers may consult if in some specific areas they are interested in more in-depth information.

2. Advanced ingredient systems for meat products

2.1. Modulations of lipid content and composition in meat products

2.1.1. Ingredients that can serve as meat fat replacers

Meat products such as emulsified or coarsely ground sausages may contain up to 37% fat (e.g. dry, cured pork salami). The high fat content of such products results in a consumption obstacle for these products by people who are prone to cardiovascular diseases and/or suffer from overweight. The World Health Organisation (WHO) recommended in an urgent call in 2003 to reduce the fat intake in the human diet (WHO, 2003). In addition to the overall quantity of fat consumed, the qualitative composition of fats in the diet has been shown to play a significant role in the level of risk of consumers to fall ill due to dietary-related chronic diseases. To promote cardiovascular health, diets should provide extremely low intakes (e.g.1%) of trans fatty

acids (hydrogenated fats). This recommendation is not only important for developed countries in the Western World, but is increasingly important in developing countries such as in Africa or South America where low-cost hydrogenated fat is more readily available at low cost than unsaturated fats and thus more frequently consumed. WHO furthermore recommends that daily diets should provide sufficient intake of polyunsaturated fatty acids (PUFAs) (e.g. 6–10% of daily energy intake). Ideally, there should be an optimal balance between intake of ω-6 PUFAs (5–8% of daily energy intake) and ω-3 PUFAs (1–2% of daily energy intake) (Nishida, Uauy, Kumanyika, & Shetty, 2004; WHO, 2003). A reduction of fat in the product can be accomplished by changing the formulation. A composition compromised of leaner raw meat, higher amounts of water, fat from plant rather than animal resources, and other ingredients such as fat replacers, in combination with altered processing conditions may allow fat profiles and concentrations in meat products to be modified.

However, reduction of fat in finely ground meat products such as emulsified, boiled sausages (frankfurter style) is extremely challenging and poses difficulties in terms of appearance, flavor, and texture. For example, if the fat content is reduced and the meat content is simultaneously increased to compensate for the loss of fat, redness values of products increase, firmness increases and water holding decreases. For this reason, a number of hydrocolloid systems with high water-binding capacity that are able to promote the formation of gels have been examined for their ability to replace fat. For example, in a study by Garcia-Garcia and Totosaus, the use of alginate, carrageenan, xanthan gum, cellulose derivates, starches and pectins has been studied (Garcia-Garcia & Totosaus, 2008). In this study, mixtures of carageenan and locust bean gum were found to be well able to improve texture and water retention, with only minor effects on sausage color. The product had acceptable sensory scores especially when compared to products that contained starch granules as fat replacers. In addition, carageenan and locus bean gums are non-digestible fibers and therefore carry a positive consumer image caused by the proven health benefits of increasing the daily intake of indigestible fibers in traditionally low fiber diets. There, a decreased risk of colon cancer, obesity, cardiovascular high blood cholesterol and coronary heart diseases may be observed (Caceres, Garcia, Toro, & Selgas, 2004; Pinero et al., 2008). Table 1 shows different examples for applications of fibers in meat products. While fibers are discussed in this chapter in the context of fat replacers, they may also act as novel texturizing agents (Pinero et al., 2008). Interestingly, incorporation of substances such as carboxymethyl cellulose in meats has been shown to have the unexpected side affect that less salt may be needed to produce an acceptable product (Ruusunen et al., 2003). However, the origin of this phenomenon is currently not well understood. In general, the full potential of fibers to reduce salt in meat products has not yet been exploited and could be an interesting area to focus on over the next years.

2.1.2. Changes in fat profiles in meat products

According to joint statements by the WHO and FAO, the recommended ratio of polyunsaturated fatty acids (PUFAs) and saturated fatty acids (SFAs) in diets should be between 0.4 and 1.0 while ω-6/ω-3 PUFA ratio should be between 1 and 4, respectively (WHO, 2003; Wood et al., 2003). Unfortunately, it is a characteristic trait of current western diets, that they are not only deficient in ω-3 PUFAs (especially long chain fatty acids) but also contain excessive amounts of ω-6 PUFAs, with an ω-6/ω-3 PUFA ratio of 15–20 as opposed to the recommended range of 1–4 (Simopoulos, 2002). For this reason, a dietary supplementation of food products with ω-3 PUFAs, and especially long chain ω-3 PUFAs such as eicosapentaenoic acid (EPA; 20:5) and docosahexaenoic acid (DHA; C22:6) has been suggested as a potential way to compensate and/or replace saturated, monounsaturated and ω-6 polyunsaturated fatty acids in foods (Jimenez-Colmenero, 2007). The two last-mentioned classes of fatty acids largely occur in plant oils. Based on current USDA data, the two most heavily consumed food oils are for example palm and soybean oil with a global consumption of 41 and 38 million tons per (US Department of Agriculture, 2009). This fact is directly responsible for the above mentioned imbalances in the ω-6/ω-3 consumption ratios.

Contrary to plant oils, fish and algae oils are one of the dietary sources that are rich in long chain ω-3 PUFAs. In particular oily cold water fish such as salmon, herring, mackerel, anchovies and sardines are major sources of ω-3 PUFAs with mackerel containing the highest amount with 2.2 g per 100 g of fish. Despite the dietary benefits of consuming ω-3 PUFAs, fish oils are difficult to include in foods. The unsaturated lipids have an increased sensitivity for lipid oxidation and the generated lipid oxidation products results in a rapid development of the characteristic "fishy" flavor of these oils. Upon inclusion in meat products, one can expect this flavor note to propagate to the raw or processed sausage. Interestingly, our own currently ongoing studies show that when the oils are included in a protein-stabilized emulsion and mixed with the meat batter, the flavor degradation is much reduced, especially after heating of the sausage. It appears that this is due to the presence of antioxidants in the spice mixes that are usually part of any sausage recipe as well as the very high protein content in meat products, which alters the propagation of the lipid oxidation.

In addition to using a delivery system such an emulsion for the ω-3 fatty acids, one can apply a variety of different processing operations such as deodorizing or refining of the oil, and applying chelators and antioxidants (Garg, Wood, Singh, & Moughan, 2006; Jimenez-Colmenero, 2007). A further alternative is to use plant oils that while not rich in EPA or DHA contain significant quantities of α-linolenic acid (ALA; C18:3). Examples of such oils are maize, soy, cotton, canola, linseed, grape seed, walnut and others (Pelser, Linssen, Legger, & Houben, 2006; Serrano et al., 2005). It should be noted though, that in order to achieve the same physiological benefits as the higher molecular weight DHA and EPA, approximately five times the amount of ALA compared to DHA and EPA needs to be consumed. This is because the body is extremely inefficient in converting ALA into the physiologically active DHA and EPA forms. Table 2 lists various approaches that have been published and are used to change fatty acid profiles, with a focus on improving in particular the ω-6/ω-3 PUFA ratio. In the most of these studies synthetic antioxidants such as BHT or BHA as well as natural plant extracts were used to prevent PUFAs from rapidly oxidizing (Ciriano et al., 2010). The need to use natural plant extracts to maintain the chemical stability of the unsaturated lipids is certainly not an issue since consumers readily accept products containing "natural", non-synthetic components. That however excludes the use of BHA and BHT, which unfortunately are much stronger antioxidants than most currently known natural extracts. For this reason, the industry's quest for natural plant extracts with a high antioxidant potential and low impact on taste and flavor continues.

2.2. Reduction of cholesterol level in meat products

The content of cholesterol in meat and meat products is influenced by a variety of different factors, such as type of meat, the cut, and the preparation conditions (broiled, pan fried, boiled etc.). Despite these variations, the concentration of cholesterol generally varies between 75 and 95 mg per 100 g of meat with the notable exception of innards such as kidney, heart, and liver that have significantly higher cholesterol contents at 300–375 mg per 100 g of meat (Chizzolini, Zanardi, Dorigoni, & Ghidini, 1999). Recommendations for daily allowances generally state that cholesterol intake should be limited to less than 300 mg per day (Chizzolini et al., 1999; WHO, 2003). Here, it is important to note that a reduced fat content and its replacement with lean meat does not necessarily decrease the amount of cholesterol in meat products (Egbert, Huffman, Chen, & Dylewski, 1991). Rather, in order to generate meat products that contain less

Table 1
Examples from literature for the applications of fibers as fat replacers in a variety of meat products.

Meat product	Type and composition of fat replacer	Fat reduction	Reference
Emulsion-type meat system	Grape seed oil (5–15%) (olive, corn, soybean, canola and grape seed oil, 10%) and rice bran fiber (2%), isolated soy protein or sodium caseinate (replacement 30–5%/30–10% back fat)	App. 30%	Choi, Choi, Han, Kim, Lee et al. (2010); Choi, Choi, Han, Kim, Lee, Kim, Jeong et al. (2009a); Choi, Choi, Han, Kim, Lee, Kim, Lee et al. (2009b)
Beef patties	Water-soluble oat fiber (Nutrim-10®) (6.7% moisture, 2.2% ash, 1.1% fat, 9.7% protein, 0.25% crude fiber, and 10% b-glucan)	App. 30%	Pinero et al. (2008)
Frankfurter	Citrus fiber and soy protein concentrate (2% as fat replacers)	50–75%	Cengiz and Gokoglu (2007)
Emulsion-type sausages, beef patties	Vegetable fibers from cauliflower, broccoli Brussels sprouts green beans green peas turnip cabbage, nettles, spinach tomato, cabbage, Swedish turnip, wild turnip, carrot, cerleriac, black radish, beetroot, rose hip, apples and pears (1% fat: 0.5–3% fiber)	2–13%	Tornberg (2005)
Sausage patties	Inulin and lupin-kernel fiber	36–37%	Archer, Johnson, Devereux and Baxter (2004)
Bologna-type Mortadella	Actilight®950P (water soluble) (2–12%) a short chain fructooligosaccharide (GFn, n64) contained 1-kestose, nystose and 1-F-fructofuranosyl-nystose	App. 40%	Caceres et al. (2004)
Bologna-type Phosphate-free sausages	Carrageenan (0.2–0.5%) or carboxymethylcellulose (0.0–0.25%)	25%	Ruusunen et al. (2003)
Salami, frankfurter, beef patties	Tapioca starch, and oat fiber or maltodextrin or milk protein	46% 60–83% 55%	Chevance, Farmer, Desmond, Novelli, Troy et al. (2000)
Bologna-type sausages	Soy fiber and plasma protein	App. 63%	Cofrades, Guerra, Carballo, Fernandez-Martin and Colmenero (2000)
Frankfurter	Oat fiber and carrageenan	55–83%	Hughes, Cofrades and Troy (1997)

cholesterol, fat *and* lean meat in raw material must be replaced by plant materials such as vegetable oils or proteins. This is because plant tissue is intrinsically lower in cholesterol than animal tissue. An exception to the rule can be found in cured loins from horse which have a significant lower concentration of cholesterol than other kinds of meats (Paleari, Moretti, Beretta, Mentasti, & Bersani, 2003).

A completely different approach to reduce cholesterol uptake is by including an interesting new component that is increasingly attracting the attention of a variety of researchers, in meat products, namely conjugated linoleic acid (CLA; octadiendecadienoic acid 18:2). CLA is naturally present in meat and has shown to be able to decrease the accumulation of cholesterol in acetylated LDL induced mouse RAW264.7 macrophage-derived foam cells presumably by enhancing lipid acceptor-dependent cholesterol efflux (Ringseis, Wen, Saal, & Eder, 2008). The main source of CLA is beef fat and bovine milk containing 3–8 mg and 5.4–7 mg per g fat, respectively (Schmid, Collomb, Sieber, & Bee, 2006). Surprisingly, the compound is not formed by the animal itself, but is formed by ruminant bacteria converting linoleic acid ingested by the animals as part of their diet. CLA is subsequently absorbed and transferred to the adipose tissue and mammary tissue. Two major isomers of conjugated linoleic acid (CLA), cis-9,trans-11 and trans-10,cis-12, show particularly pronounced biological activities. The most common CLA isomer found in beef is cis-9 and trans-11 (Schmid et al., 2006).

To achieve significant reduction in cholesterol levels though, concentrations higher than those naturally present in meat must be consumed. Thus, studies have focused on increasing the concentration of CLA in meats. For example, the CLA content of meat increased with a supplementation of the animal feed by linoleic acid (Dunshea, D'Souza, Pethick, Harper, & Warner, 2005; Intarapichet, Maikhunthod, & Thungmanee, 2008). In the case of dairy products, processing appears to be beneficial as cooking has been shown to lead to increases in CLA content (Herzallah, Humeid, & Al Ismail, 2005). In addition to the cholesterol-lowering functionality, CLA has been associated with anticancinogenic, antidiabetic, and antiatherogenic effects, as well as a strengthening of the immune system, bone metabolism, and improvements in body composition (Schmid et al., 2006). Recent studies have suggested that CLA could be used to reduce body weight by improving the lean mass. This effect appears to be based on dietary CLA increasing energy expenditure of the body as well as increasing fatty acid β-oxidation (Park & Pariza, 2007). In this respect, CLA may be a major functional food ingredient that food manufacturers will need to take better advantage of in the future if the same health benefits that have been found in mice, rat and rabbit studies are shown to occur in humans as well (Arihara, 2006a,b). Regardless of these promising results, substantially more studies will be needed to properly assess the impact of CLA on human health. To date, the risk factors that accompany an increased consumption of

Table 2
Literature examples of non-meat fat based formulations of meat products.

Meat products	Composition of added oil	Oil content [%]	Fat content [%]	n-3 PUFA [%]	MUFA [%]	n-3/n-6 PUFA	PUFA/SFA	Reference
Frankfurters	Corn, sodium caseinate	6.7	10	0.03	3.1	132	1.74	Bloukas and Paneras (1993)
	Olive, sodium caseinate	6.7	10	0.05	6.8	14.8	0.33	
	Sunflower, sodium caseinate	6.7	10	0.02	2.9	215	1.95	
	Soybean, sodium caseinate	6.7	10	0.44	2.5	7.7	1.79	
Dry fermented sausages	Fish oil extract/soy protein isolate	0.5–1.1	29–33	0.56–1.01	12.6–13.8	7.7–5.3	0.5–0.58	Muguerza, Ansorena and Astiasaran (2004)
Dry fermented sausages	Desodorize fish oil/soy protein isolate	3.3	27	1.41	12.0	3.0	0.56	Valencia, Ansorena and Astiasaran (2006)
Dutch style fermented sausages	Fish oil (encapsulated)	4.5	39	0.38	17	9.59	0.31	Pelser et al. (2006)
	Flaxseed (encapsulated)	4.5	40	3.82	13.34	1.06	0.59	
	Flaxseed/sodium caseinate	6	35	4.33	13.61	0.87	0.69	
	Flaxseed/soy protein isolate	3–6	40	2.38–4.72	16.4–15.4	1.93–1.05	0.49–0.71	
	Canola/soy protein isolate	3–6	39	0.75–0.89	17.9–18.0	6.94–5.12	0.42–0.48	
Dry fermented sausages chorizo	Linseed	3.3	30–32	2.44	11.8	1.7–2.1	0.6–0.7	Ansorena and Astiasaran (2004)
Dry fermented sausages	Linseed/algae (3:2) (2:3)	6.25	32.9	6.86	43.68	1.96	0.58	Ciriano et al. (2010)

CLA especially with respect to coronary heart diseases as a result of exposure to these specific trans fatty acid isomers have not yet been properly assessed (Park, 2009). Despite these uncertainties, studies have begun that looked at the possibility of fortifying meats with CLA. For example, Juarez et al. (2009) added CLA (6–7% of total fatty acids) to sausages and studies the effect that grilling had on the CLA content. They reported similar levels in grilled sausages and in raw sausages.

Another component that has been studied in the wake of CLA is L-carnitine (3-Hhydroxy-4-trimethylammonio-butanoate). The compound appears also to be involved on the ß-oxidation of fatty acids that is needed to produce energy and reductions in the level of cholesterol have been reported for L-carnitine as well (Solfrizzi et al., 2006). The action of this compound has been attributed to it being a substrate for the enzyme carnitine palmitoyltransferase, that plays a key role in the regulation of fat and carbohydrate metabolism. Moreover, L-carnitine appears to be essential in the body absorbing calcium to improve skeletal strength and to form lean muscle mass (Arihara, 2006a,b). Carnitines have shown to possess significant antioxidant potential, thereby providing a protective effect against lipid peroxidation of phospholipid membranes and against oxidative stresses induced at the myocardial and endothelial cell level (Guelcin, 2006). L-carnitine is present at substantial levels in skeletal muscles, especially in beef (3320–1870 mg/kg dry matter) and in pork (135–830 mg/kg dry matter) (Knuettel-Gustavsen & Harmeyer, 2007). Because of its potential to act as an antioxidant, its ability to maintain meat quality was assessed by Djenane, Martinez, Sanchez-Escalante, Beltran, and Roncales (2003), who applied the compound to the surface of beef steaks that had been challenged with ascorbic acid. Disappointingly, the quality of the beef steak treated with L-carnitine was not significantly improve compared that of a control steak without L-carnitine.

Finally, frankfurters and cold cuts enriched with non-esterified plant sterols from tall oil, potassium, calcium and magnesium reduced the serum's total cholesterol concentration in hypercholesterolemic subjects when the intake of sitosterols was 2.1 g/day. The above described combination of plant sterols and minerals was taken as part of a habitual Finnish diet. At lower doses of sistosterol, no effect on cholesterol levels was found (Tapola, Lyyra, Karvonen, Uusitupa, & Sarkkinen, 2004).

2.3. Salt and sodium reduction in processed meat products

Sodium chloride in meat products is an essential ingredient providing simultaneously a number of different functionalities. Firstly, salt is being used as a preservative to prevent the spoilage of perishable foods, of which meat products are characteristic example. The reduction of water activity due to the addition of salt and the presence of ions exerting osmotic pressure effects on the microorganisms increase the shelf life of processed meat. Thus, when the salt content in meat products is reduced below typically used levels, the product has a shorter shelf life or may no longer be safe without addition of other preservatives (Madril & Sofos, 1985). Secondly, salt is a critical component to give meat products their characteristic flavor. In this respect, salts have found to enhance typical meat flavor in processed meat. Thirdly, salt plays a key role to create the desired texture of a processed meat product. This is because the level of salt directly influences the solubility of the myofibrillar meat proteins myosin and actin. Changes in solubility in turn influence water-binding capacity that is generally improved with salt. When salt is added and proteins are solubilized, viscosity of meat batters increases, partially because the proteins have a chance to increasingly interact to form protein networks and partially because they are now able to stabilize the interface of meat fats thereby forming a stable emulsion (Desmond, 2006, 2007).

Despite these key functionalities that are essential for the manufacturing of many meat products, there is increasing pressure from a large number of organizations to reduce both salt and sodium content in meats. This is because a direct relationship between an excessive intake of sodium and an increased incidence of hypertension has been demonstrated in various scientific publications (Dahl, 1972; McGregor, 2007). Hypertension is one of the main risk factors for cardiovascular disease. The WHO recommends as little as 5 g of salt per day, which is equivalent to 2 g sodium per day (WHO, 2003). The consumption of meat and meat products contributes about 16–25% to the total daily intake of sodium chloride and thus is second only to bread with respect to salt levels (WHO, 2003). In order to lower the content of salt, there are three potential solutions (Desmond, 2006, 2007). Firstly, sodium chloride may be replaced by potassium chloride. This method is in fact the most commonly used method to date. However, potassium chloride has a slightly bitter taste and to prevent the product from having unacceptable sensory properties, masking substances have to additionally be added to the products. Newer studies have attempted to use complex mixtures of alternative salts to mediate some of the negative sensory effects. Secondly, flavor enhancer may be added to the meat product. The flavor enhancers while themselves not having a salty taste may in combination with salt increase the saltiness of the product. For example, carboxymethyl cellulose and carrageenan in combination with sodium citrate have been shown to enhance saltiness in frankfurters (Ruusunen et al., 2003). Thirdly (and this is a relatively new and not yet fully explored approach), the physical structure of sodium chloride could be altered. A change in particle size of undissolved salt crystals could lead to a more rapid dissolution behavior in the mouth thereby yielding a more pronounced salty taste of the product. However, to prevent excessive growth of salt crystals, this approach may need to be combined with an additional modification changing the physical state of salt from a crystal to a glass. Angus (2007) reported that in this case, particle size of table salt crystals that ranged from 200 to 500 µm could be reduced to 5–10 µm when the salts existed in an amorphous cubic-glass form.

Table 3 shows selected examples of various formulations used to reduce the salt content in meat products. The most common substances used in combination with sodium and potassium chloride are phosphates, salts of organic acids or carbohydrate such as trehalose or sucrose. Phosphates in addition to promoting saltiness simultaneously improve the water-binding capacity and cooking loss. Nevertheless, much work still needs to be done to find a suitable replacement for the multifunctional sodium chloride. A better solution will likely come from addressing each of the three main technological functions of sodium chloride, saltiness, solubilization of proteins and preservation, separately. For example, processing oriented approach could be developed to promote a solubilization of proteins at lower salt levels e.g. through the application of high-intensity ultrasound. In terms of preservation, alternative antimicrobial compounds, such as naturally occurring secondary plant metabolites could be used to enhance food safety and prolong shelf life of products.

2.4. Nitrite reduction or replacement in meat products

Nitrite is one of the staple ingredients in meat product manufacturing. Rock salts that naturally contain low levels of nitrites have been known for centuries to be excellent preservative agents. Nitrite in meat products inhibits the growth of *Clostridium botulinum* and thereby the formation of the neurotoxic proteins that are commonly known as botulinum toxin. Nitrite also contributes to the development of flavor in cured meat products and is responsible for the formation of the characteristic pink/red color in cured and smoked products. Finally, nitrite retards the development of rancidity and off-odors and flavors during storage. Regardless of the technological benefits, a reduction in the use of nitrites has become a key issue for the industry. This is because nitrite can under certain circumstances

Table 3
Literature examples for approaches to reduce the sodium/salt levels in various meat products.

Meat product	Composition of mixtures	Sodium/salt reduction	Reference
Chicken nuggets	KCl, citric acid, tartaric acid, sucrose, apple pulp (8–12 g/100 g)	40%	Verma, Sharma and Banerjee (2010)
Meat emulsion-type model	NaCl (0.5%), edible seaweeds (Sea spaghetti, Wakame, Nori)	75%	Lopez-Lopez, Cofrades, Ruiz-Capillas and Jimenez-Colmenero (2009)
Cooked pork	K-lactate, Na-diacetate (Purasal®Opti.Form PD4), phosphate	20–40%	Devlieghere, Vermeiren, Bontenbal, Lamers and Debevere (2009)
Cured loins	NaCl (45–75%), KCl (25–50%), Ca_2Cl (15–20%), Mg_2Cl (5–10%)	25–55%	Alino, Grau, Baigts and Barat (2009)
Frankfurters	NaCl (0.5%), KCl (0.5%) edible seaweeds, algae oil (olive oil)	50–75%	Lopez-Lopez, Cofrades and Jimenez-Colmenero (2009)
Meat products	Tyrosinase, NaCl (>1.2%–<2%) and Na_3 diphosphate (>0.1–<0.2)	40–50%	Lantto, Autio, Kruus and Buchert (2007)
	Na gluconate (22–33%), KCl (22–33%), NaCl (>45%)	40–60%	Pfeiffer, Scholten and Oellers (2007)
	KCl, mono-K or Ca-phosphate, K citrate	25%	Vadlamani (2008)
Marinated chicken, beef, pork	Trehalose (>0 <1.5%), NaCl and KCl (50%)	20–50%	Ganesan, Zoerb, Mullally, Weigle and Adams (2007)
Fermented sausages	NaCL (50%), KCl (50%) or KCl (40%) + K-lactate (10%)	50%	Guardia, Guerrero, Gelabert, Gou and Arnau (2006)
Salami, sausages	NaCl (1.5%), sodium poly/diphosphate, calcium gluconate	App. 35%	Boicean (2005)
Frankfurter	Transglutaminase, caseinate, KCl and fiber	85–90%	Colmenero, Ayo and Carballo (2005)
Ground meat patties	NaCl (0.6–0.8%), tetra-potassium diphosphate, maltodextrin	30–48%	Ruusunen, Vainionpaeae, Lyly, Laehteenmaeki, Niemistoe et al. (2004)
Bologna-type phosphate-free sausages	1.2–1.3% NaCl and 0.22–0.35% sodium citrate, or 0.2–0.5% carrageenan or 0.0–0.25% carboxymethylcellulose	20–25%	Ruusunen et al. (2003)
Dry cured loins	KCl, K-lactate	40%	Gou, Guerrero, Gelabert and Arnau (1996)

(low pH and high temperature) react with amines to form nitrosamines, compounds that have shown in variety of animal studies to be carcinogenic (Jakszyn & Gonzalez, 2006). While currently approved levels in meat products are deemed safe, there is nevertheless pressure coming from the consumer side to further reduce or eliminate the use of nitrate.

2.4.1. Decreased oxidation by the use of novel antioxidants

The oxidation of lipids in meat products is a key problem that reduces shelf life of frozen meats, fermented processed meat such as dry sausages, and cured raw ham. In precooked meats, lipid oxidation leads to detrimental changes in the flavor of the reheated, precooked products after refrigerated storage, a phenomena known as "warmed-over-flavor". Here, both lipids and proteins may be oxidized in a series of radical reactions that involve initiation, propagation, and termination steps with simultaneous formation of free radicals (Ladikos & Lougovois, 1990). In meat lipids, the formation of lipid oxidation products from unsaturated fats is initiated by singlet oxygen converted from triplet oxygen or a catalyst and triplet oxygen. Further reactions yield hydroperoxides that act as strong oxidizing agents (ROS — reactive oxygen species) (Kubow, 1992). Metal catalysts such as iron and copper are key elements involved in the breakdown of these compounds. When hydroperoxides are degraded, highly reactive free radicals are generated that in turn react with the double bonds of other unsaturated lipid acids thereby producing more radicals that further propagate the chain reaction of lipid oxidation (Kubow, 1992). From a sensory point of view, a large number of small molecular weight degradation products that are often volatile are formed. These compounds are ultimately responsible for the development of a rancid off-flavor. In addition, some of these oxidation products have shown to possess mutagenic and carcinogenic potential (Gao et al., 1987), making an extensive oxidation of meat and meat products a health problem.

Oxidation processes in meats and meat products can be reduced by eliminating oxygen and light during the storage of the products. In addition, ingredients with antioxidant potential may be added to the products to scavenge free radicals and thus terminate the chain reaction. Compounds such as vitamin E, lycopene or lutein have also shown to not only reduced lipid oxidation but also to have health benefits. For example, lutein together with zeaxanthin has been associated with the maintenance of good eye health due to its ability to reduce the risk of Age Related Macular Degeneration (AMD). A fortification of meat products with these substances may thus be highly desirable to create a new class of meat based functional foods (Granado-Lorencio et al., 2010).

A reduction of oxidation processes in meat and meat products can also come from the application of chelators that bind pro-oxidants as such as iron or other metals thereby inhibiting the formation of radicals by metal catalysis. Well-known chelators are for example ethylenediaminetetraacetate (Calciumdinatrium-EDTA, E 385), citrate, polyphosphates or peptides (Ahn, Wolfe, & Sim, 1993). More recently, polyphenolic compounds such as catechins have been investigated for their potential to inhibit lipid oxidation in meat. For example, Tang et al. (2006) study the effects of added tea catechins on the color stability and lipid oxidation in minced beef patties. The authors reported consistently lower lipid oxidation; in tea catechin treated products compared to controls, after storage under both aerobic and MAP packaging conditions for several days.

Additional enhancement of meat and meat product quality can come from addition of antioxidants that stabilize free radicals thereby delaying the propagation of lipid oxidation reactions. The radicals react with antioxidants often possessing an aromatic ring structure thereby sequestering them and making them unavailable for further reaction with the double bonds of unsaturated fatty acids. The cascade reaction is thus terminated by the addition of such free radical stabilizers (Alamed, Chaiyasit, McClements, & Decker, 2009). Typical additives are for example propyl gallate, butylated hydroxyanisol (BHA), butylated hydroxytoluene (BHT), tertiary butyl hydroquinone (TBHQ), nitric oxide from sodium nitrite, and naturally occurring substances such as α-tocopherol (vitamin E), ascorbic acid (vitamin C), spices and spice extracts such as rosemary (*Rosmarinus officinalis* L.), oregano (*Origanum vulgare* L.), or sage (*Salvia officinalis* L.) (Boon et al., 2008; Fernandez-Lopez et al., 2003; Hernandez-Hernandez, Ponce-Alquicira, Jaramillo-Flores, & Guerrero Legarreta, 2009). The latter listed plant extracts are typically obtained by maceration of

plant matter with organic solvents or by supercritical CO_2 extraction (Oberdieck, 2004). In contrast to synthetic antioxidants, the use of natural antioxidants from spices is increasing since their application is less stringently regulated in most countries around the world. Active essential oil compounds in rosemary, oregano, borage and sage are for example phenolic diterpenes, derivates of hydroxycinnamic acid, flavonoides and triterpenes (Oberdieck, 2004; Ryan et al., 2009; Sanchez-Escalante, Djenane, Torrescano, Beltran, & Roncales, 2003; Sanchez-Escalante et al., 2003). For rosemary, sage and oregano, the most active substances with a high antioxidant potential are carnosic acid, carnosol, and rosmarinic acid (Oberdieck, 2004). Interestingly, (see also below), these compounds also often display antimicrobial activities making them useful to enhance food safety by inhibiting the growth of food pathogens. In Table 4, an overview over use and effect of natural antioxidants in meat and meat products is shown. Results have been classified according to their TBARS (thiobarbituric acid reactive substances) reduction.

While non-meat intrinsic antioxidants such as tocopherols, glutathione and others have been added to meat, intrinsic peptides with antioxidant activities have been found in skeletal muscle. Prominent examples of such peptides are carnosine (β-alanyl-L-histidine) and anserine (N-β-alanyl-1-methyl-L-histidine). Both are abundantly present in meats (Fu et al., 2009). Pulse radiolysis studies have been used to investigate their antioxidant capacities at different pH in aqueous solutions. The rate constants for the reaction of the hydroxyl radicals with carnosine at neutral pH were $5.3\times10^9\ M^{-1}\ s^{-1}$ at 300 nm, and $4.1\times10^9\ M^{-1}\ s^{-1}$ at 400 nm, respectively (Fu et al., 2009). Concentrations of carnosine in meat range from 0.5 g per kg of chicken thigh to 2.7 g per kg of pork shoulder (Arihara, 2006a). The addition of carnosine at 1–1.5% prior to blending of ground buffalo meat improved the quality and extended the shelf life to up to 8 days under refrigerated storage (Das, Anjaneyulu, & Biswas, 2006). Carnosine (78–94%) also had a notable effect on improving metmyoglobin-reducing activity and thus produced better color stability at a low concentration. In combination with α-tocopherol (0–12%) and tea catechins (3–19%), carnosine substantially decreased lipid oxidation and stabilized color of raw beef patties (Liua, Dai, Zhua, & Li, 2010). Surface application of carnosine or ascorbic acid in beef steaks packaged at a modified atmosphere ($70\%\ O_2+20\%\ CO_2+10\%\ N_2$) resulted in an effective delay of oxidation (Djenane et al., 2003). In addition to their antioxidant properties both carnosine and anserine have been investigated for their potential to be used in functional foods. The components apparently accelerated wound healing and prevent diseases associated with stress. Of the two, anserine has shown to be more effective since it resists digestions (Arihara, 2006a).

Another effective and relatively uncontroversial approach of reducing lipid and myoglobin oxidation in fresh meat and meat products is a vitamin E (all rac-tocopheryl acetate) fortification of animal feed (Houben, Eikelenboom, & Hoving-Bolink, 1997; Houben, Van Dijk, Eikelenboom, & Hoving-Bolink, 2000). Dunshea et al. (2005) for example reviewed the effects of dietary factors and other metabolic modifiers on quality and nutritional value of meat and stated the positive effect of a supplementation of vitamin E at levels of 100–200 mg/kg feed on the quality of meat products from different meat of animals. All studies reviewed by the authors appeared to show significantly lower muscle oxidation when vitamin E was added to feeds for periods ranging from 84 to 130 days pre-slaughter.

Finally, environmental factors may play a role in lipid oxidation. While oxidation of lipids occurs mainly in the lipophilic part of meat products, oxidation products such as small molecular weight lipid peroxides and free radicals are substantially more water soluble and thus translocate to more hydrophilic parts of the meat product. This causes the water content of meat products to indirectly influence the lipid oxidation. For example, lipid oxidation is at its highest at either very high or very low a_w-values. This is because the movement of pro-oxidants increases the more "unbound" water available. In contrast to that, at low water contents, pro-oxidants may increase in concentration to the point where oxidation again increases. For this reason, a combination of hydrophilic chelating agents and lipophilic radical scavenging antioxidants appears to be best suited in preventing of lipid oxidation (Alamed et al., 2009). Finally pH of chill-stored meat products that had been pre-frozen had a noticeable impact on lipid oxidation. A lower pH value tends to result in more rapid oxidation of lipids (Hansen et al., 2004). The authors thus concluded that the pH should be in a narrow range so that both microbiological safety and meat quality such as lipid oxidation can be controlled.

2.4.2. Increased shelf life by the use of nitrite substitutes

As indicated above, one of the most important functionalities of nitrite is its ability to inhibit the growth of food pathogens in meat products. The inhibition of bacteria by nitrite has been attributed to a variety of different mechanisms including the inhibition of oxygen uptake, oxidative phosphorylation and proton-dependent transport (Davidson, Sofos, & Branen, 2004). Nitrite was also found to inhibit a number of enzymes that are essential to the metabolism of bacteria such as aldolase. Moreover, nitrite generally causes a breakdown of the proton gradient in bacteria needed to generate ATP. The many different effects that addition of nitrite has on the metabolism of food pathogens are the key reason why the compound is so effective. It is also the reason, why nitrite is so difficult to

Table 4
Effect of different antioxidants or plant extracts in meat systems on the formation of thiobarbituric acid reactive substances (TBARS).

Meat product	Substances/plant extract	Conditions	TBARS reduction [%]	References
Cooked beef meat	Propyl gallate (0.2 mmol/kg)	4 °C, 72 h	92	Alamed et al. (2009)
	Gallic acids (0.2 mmol/kg)		63	
	Coumaric acid (0.2 mmol/kg)		13	
	Ferulic acid (0.2 mmol/kg)		12	
	TBHQ tert-butylhydroquinone (0.2 mmol/kg)		85	
	Rosmarinic acid (0.2 mmol/kg)		App. 30%	
	α-Tocopherol (0.2 mmol/kg)		App. 28%	
	Ascorbic acid (0.2 mmol/kg)		(−10%) pro-oxidant	
Ground buffalo meat	Carnosine (0.5%)	4 °C ± 1 °C, 6 d	38	Das et al. (2006)
	Carnosine (1%)		40	
	Carnosine (1.5%)		43	
Beef patties	Rosemary extract (0.1%),	4 °C ± 1 °C, 6 d modified atmosphere	App. 85%	Sanchez-Escalante, Djenane, Torrescano, Beltran, and Roncales (2003)
	ascorbic acid (0.05%)		App. 83%	
	Rosemary extract		App. 82%	
	Oregano extract (0.05%)		App. 85%	
	Borage meal (1%, 2%)		Pro-oxidant	
	Ascorbic acid (0.05%)			
Cooked pork meat	Rosemary extract	4 °C ± 1 °C, 6 d	App. 95%	Fernandez-Lopez et al. (2003)
	Hyssop extract		App. 95%	

replace as a preservative. Since nitrite acts on multiple sites simultaneously, it is very difficult for food pathogens or food spoilage organisms to adapt to its presence. Small concentrations of nitrite are sufficient to cause a broad spectrum inhibition of food pathogens.

2.4.2.1. Ingredients that contain nitrate. One method to avoid the direct addition of nitrite to meat is to instead add ingredients that have a natural high nitrate content. This method is used in the production of organic versions of cured meats (Sebranek & Bacus, 2007). Organic "uncured" meat products exhibit all typical sensory properties (color, appearance, and shelf life stability) of nitrite-cured meat products. Ingredients that have been used to manufacture "nitrite-free" cured meat products include unrefined sea salt, turbinado sugar (a raw sugar that is produced by first evaporating sugar cane juice followed by the removal of surface molasses by centrifugation), flavors and spices, celery, carrot, beet and spinach juice. While it had been initially suggested that the technological effect of these ingredients may be due to their residual nitrite content, their nitrite level was either extremely low (e.g. 0.3–1.7 ppm for sea salt), or non-existent. Vegetable and spice matter instead contain high levels of nitrate that during curing can be converted by nitrate-reducing bacteria into nitrite. For example, Sebranek and Bacus (2007) reported nitrate levels of 2114 ppm in celery juice and 3227 ppm in spinach juice. When the juice was dried to produce a commercial celery juice powder, levels of nitrate climbed to 27,462 ppm (Sindelar, 2006). Meat products produced with celery powder did initially not contain any nitrite. After curing for 10 days at room temperature nitrate levels decreased by 14–22% and 128–189 ppm of nitrite was found in the products. Fischer, Bristle, Gehring, Herrmann, and Gibis (2005) similarly reported that with a nitrate-reducing starter culture (*Staphylococcus carnosus* ssp. *utilis*) and addition of a spice mixture containing a defined content of nitrate, similar color, color retention and acceptable flavor developments in meat products could be achieved. Upon inoculation of products with *Listeria innocua*, no growth was detected and cell numbers of enterobacteriaceae remained constant (Fischer, Bristle, Ulmer, & Wolf, 2005). It should be noted though, that this process is highly dependent upon the effectiveness of the starter culture to convert nitrate to nitrite. Here, process control is of critical importance. For example, an increase in nitrate conversion rates has been described by Casaburi, Blaiotta, Mauriello, Pepe, and Villani (2005) when starter cultures were allowed to grow at 30 °C instead of 15 °C.

2.4.2.2. Novel naturally occurring antimicrobials. An alternative to the use of nitrite is to add naturally occurring antimicrobials to meat products. Antimicrobial agents have been defined as "chemical compounds present in or added to foods, food packaging, food contact surfaces, or food processing environments that inhibit the growth of, or inactivate pathogenic or spoilage microorganism" (Davidson et al., 2004). Naturally occurring antimicrobials in contrast to traditional or synthetically-derived antimicrobials are compounds that may be present in spices, herbs or their essential oils including terpenes, coumarins, and flavonoids (Kim, Marshal, & Wei, 1995). Other naturally occurring antimicrobials may be obtained from microbial (e.g. nisin), or animal sources (lysoyme, antimicrobial polypeptides (AMPs)) (Gaysinsky & Weiss, 2007). Because of the broad spectrum of activity of nitrite, a replacement by a single antimicrobial is difficult and a combination of antimicrobials is required (Sofos, 2008). For example, Ntzimani, Giatrakou, and Savvaidis (2010) added EDTA, lysozyme, rosemary and oregano oil to chicken meat stored in vacuum packages at 4 °C. They showed that combinations were effective against the growth of Gram-positive bacteria Gram-negative bacteria and to a lesser degree yeasts. Combinations of nisin with oregano oil were tested in minced sheep meat during refrigerated storage (Govaris, Solomakos, Pexara, & Chatsopoulou, 2010). Growth of *Salmonella* Enteritidis was inhibited after the addition of 500–1000 IU/g of nisin and 0.6–0.9% oregano oil. Muench, Maddock, and Wulf (2008) used sodium lactate, sodium diacetate, and sodium citrate to prevent spoilage in natural casing frankfurters. Blends of 55.7% sodium lactate with 4% sodium diacetate at a concentration of 3% did not negatively impact quality attributes. No spoilage occurred during 15 weeks of storage at 3 °C in the absence of light. When the antimicrobial activity of lysozyme (195 $\mu g/cm^2$) and nisin (260 $\mu g/cm^2$) combinations at a mixing ratio of 1:3 of nisin to lysozyme were studied against *Carnobacterium* sp 845 and *Brochothrix thermosphata* B2 on lean pork tissue, growth reduction during >20 days of storage of up to 3 log units compared to untreated samples was found (Nattress, Yost, & Baker, 2001). Finally, Kanatt, Ramesh, and Sharma (2008) studied the effectiveness of combinations of chitosan and mint for meat and meat products. They reported both antimicrobial as well as antioxidant activities of the combination. Antioxidant properties were attributed to the mint extract while antimicrobial activities were attributed to chitosan. Chitosan-mint mixtures (0.05%) inhibited growth of *S.* typhimurium, *Pseudomonas*, *E. coli*, *B. cereus* and *S. aureus* during storage at 0–3 °C for 28 days. An assay of the total bacterial counts in pork salami during chilled storage showed that mix-containing salami had on average 1.5 Log CFU/g cells less than an untreated control.

These studies show that the use of alternative antimicrobials or their combinations can control growth of food spoilage organisms and food borne pathogens in meat and meat products. Recent developments in controlling the growth of microorganisms in other products by the use of delivery systems for antimicrobials should be taken into account (Gaysinksy, Davidson, Bruce, & Weiss, 2005a,b; Gaysinsky, Davidson, McClements, & Weiss, 2008; Gaysinsky, Taylor, Davidson, Bruce, & Weiss, 2007; Taylor, Davidson, Bruce, & Weiss, 2005; Taylor, Gaysinksy, Davidson, Bruce, & Weiss, 2007; Taylor, Bruce, Weiss, & Davidson, 2007; Were, Bruce, Davidson, & Weiss, 2004a,b). These studies have demonstrated that problems of incompatibilities of antimicrobials with food matrix properties can be overcome by delivering naturally occurring antimicrobials in nano- and microscalar carrier systems such as emulsion, liposomes, microemulsions, hydrogel particles and others. Future studies may thus want to focus on determining the applicability of such systems to meat and meat products with the expressed objective of replacing or reducing nitrite.

2.4.2.3. Sanitizing meat surfaces. Sanitation of meat surfaces prior to grinding or prior to the production of batters may improve the control of growth of food borne pathogens. With the emergence of continuous processing methods for the production of meat products, the introduction of aseptic processing techniques for meat products could soon become feasible. Thus, applications such as electrolyzed oxidizing water (Fabrizio & Cutter, 2005), high pressure in combination with antimicrobials (Hugas, Garriga, & Monfort, 2002), irradiation and light pulses (Aymerich, Picouet, & Monfort, 2008), and surface sanitizers such as chlorine dioxide, cetylpyridinium chloride, and lactic acid (Jiminez-Villarreal, Pohlman, Johnson, & Brown, 2003a, b) could extend shelf life of meats. Another surface treatment that is known to improve shelf life is the application of marinates (Björkroth, 2005). Marinates can be oil-in-water emulsions that contain spices and flavors in the lipid phase and salt and acids in the aqueous phase. They are often used in combination with modified atmosphere packaging. Björkroth demonstrated that applications of marinates may impact growth of psychotrophic bacteria, but pointed out that the buffering capacity of meat may neutralize pH of acidic marinates.

In summary, while the above described methods may individually not be able to completely replace nitrite, combinations of these approaches may be able to do so or at least reduce required levels.

2.5. Enzymes as novel texture modifiers

Novel enzymes from microbial, plant and animal sources may be used to modify texture of meats and meat products. In principal, enzymes may be used in two different ways to alter structure of meat

and meat products. First, enzymes may catalyze breakdown of covalent bonds in proteins thereby generating smaller peptide fragments or amino acid. This structure breakdown may increase the tenderness of meat. Second, enzymes may promote the formation of new covalent bonds between meat proteins. In meat gels, such enzymes may enhance firmness and water holding capacity of gels.

2.5.1. Structure breakers

Rapid degradation of the intrinsic structure of proteins in meats (in particular intermediate filament proteins) by proteolytic enzymes is a well-known process that contributes to an increase in water holding capacity and tenderness of products (Huff-Lonergan & Lonergan, 2005). In meats, intrinsic proteases degrade specific sets of myofibrillar and cytoskeletal proteins under post-mortem conditions. The endogeneous calpain system has been shown to play a key role in regulating proteolysis of protein substrates such as desmin, synemin, talin and vinculin (Bilak et al., 1998). Two well-known isoforms of calpains, μ-calpain and m-calpain are both calcium-dependent cystein proteases that are regulated by an endogeneous inhibitor, calpastatin. The complex interplay between calpain and calpastatin in post-mortem muscle has been associated with large differences in meat tenderness that are often observed (Goll, Thompson, Li, Wei, & Cong, 2003). This interplay is affected by environmental conditions in the tissue such as pH, ionic strength and temperature (Maddock, Huff-Lonergan, Rowe, & Lonergan, 2006). Post-mortem muscle changes such as depletion of ATP, aerobic to anaerobic metabolism shifts causing decreases in pH, rise in ionic strength due to the inability of cells to maintain functionality of ion pumps, and loss of reducing conditions, contribute to the difficulty of precisely controlling proteolysis. While water holding capacity in meat products such as batters may be improved, it is difficult to accurately regulate proteolytic myofibrillar protein breakdown. Gel structures may be less orderly and products less firm and elastic after heating (Cofrades, Banon, Carballo, & Colmenero, 2003).

Rather than relying on the activity of intrinsic proteases, non-intrinsic proteases from microbial sources may be added to meats and their products. Traditionally, proteases derived from plants have been used. Examples of cystein proteases from plants are (a) papain present in papaya (*Carica papaya*) and mountain papaya (*Vasconcellea cundinamarcensis*) and (b) bromelain from plants of the family Bromeliaceae to which pineapple belongs. These plant-derived cystein proteases are non-specific in their action and thus do not only tenderize but also degrade the texture of meat, resulting often in over-tenderization. More recently, newer, more specific proteases have been used. For example, Benito, Rodriguez, Acosta, and Cordoba (2003) reported on the use of a novel fungal extracellular protease with respect to texture changes in whole pieces of pork loin. The EPg222 protease had been isolated from *Penicillium chrysogenum* on dry-cured ham. Authors reported that incubation of pork loins with 0.012 mg/ml of the enzyme for up to 32 days under sterile conditions significantly decreased hardness as measured by instrumental texture analysis by a factor of 3 (from 54.5 N in control loins to 14.2 N in treated pork loins after 32 days). The authors concluded that the externally applied enzyme was able to counteract increases in hardness that are results of protein denaturation in dry-cured hams. They even suggested that the created texture that may be "too soft" for such products. Qihe, Guoqing, Yingchun, and Hui (2006) reported on the use of a new elastase from *Bacillus* sp. EL31410 in beef meat. Elastase is an enzyme that breaks down elastin in connective tissue. The authors found that a 4 h treatment of freeze-dried meats that had been dipped in 1% elastase solutions led to a 30% decrease in relative hardness after storage for 96 h. In contrast, a similar treatment with papain decreased the relative hardness by 70%. Papain treated meats had better tenderness sensory scores but lower scores of juiciness and flavor compared to elastase treated meats. Scanning electron microscopy studies revealed that in contrast to papain, a very selective degradation of the myofibrillar structure had been taken place with elastase. Gerelt similarly described that proteases from *Aspergillus* used for soybean sauce production improved sensory scores of juiciness and taste. There, meat had first been osmotically dehydrated and then treated with a 1% protease solution for 3 h. Under the electron microscopy, authors observed extensive degradation of myofibrillar structure due to a proteolytic removal of Z-lines.

Based on these results, it may be interesting to look at other alternative sources of proteases. Collagenases and elastases can for example be found in fish and aquatic invertebrates, and those enzymes may have very different specificities compared to those found in mammalian muscles (Shahidi & Kamil, 2001). Gastric elastases have been recovered from marine and fresh water species such as carp, catfish and Atlantic cod with the ability to rapidly degrade elastin.

2.5.2. Structure makers

In contrast to the above described "structure breakers", enzymes may also be used to form covalent bonds between proteins. The most prominent enzymes that belong to this class are transglutaminases (TGase). Generally, transglutaminases are calcium-dependent enzymes that catalyze acyl transfer reactions with the ε-amino group of lysine and lysyl residues acting as acyl acceptors and γ-carboxamide groups of glutamine acting as acyl donors (Kumazawa, Nakanishi, Yasueda, & Motoki, 1996). In the process, ε-(γ-glutamyl)-lysine cross-links are formed. Microbial transglutaminase has been successfully used to improve the functional properties of meat gels by catalyzing formation of glutamyl-lysine bonds in myosin, myosin and actin, myosin and fribonectin and fibrin and actin (Kahn & Cohen, 1981). Herrero, Cambero, Ordonez, De la Hoz, and Carmona (2008) carried out texture profile analysis (TPA) and Raman spectroscopy studies on the effect of MTGase in minced water-meat homogenates. TPA indicated that hardness, springiness and cohesiveness were significantly higher ($p > 0.05$) in enzyme-containing homogenates and increased with increasing MTGase concentration. Raman spectroscopy suggested that this was because substantial changes in secondary structure of meat proteins occurred. For example, α-helix content decreased while content of β-sheets and turns increased. The authors concluded that this may allow manufacturers to produce meat products with high water-binding capacities without phosphates and with less salts. Tseng, Liu, and Chen (2000) similarly suggested that high quality, low salt chicken meat balls could be formulated with the help of TGase. There, gel strength of meat balls increased as the concentration of TGase in the batter increased from 0.05 to 1%. Addition of TGase did not adversely affect color of the product. Scanning electron microscopy images showed higher order in meat gels compared to those that were TGase free. Trespalacios and Pla (2007) suggested that TGase may help counteract effects of softening of low-fat protein gels obtained by pressure rather than heat treatment. There, microbial TGase was added to chicken batters at 0.3%. These were then treated at 500 MPa for 30 min at 40 °C followed by a 5-minute heating to 75 °C to inactive the enzyme. Confocal microscopy revealed a more compact and homogeneous gel microstructure in TGase/pressure treated samples. Hardness and chewiness increased compared to controls. Nielsen, Petersen, and Moller (1995) reported that cross-linking of meat proteins by TGase depended on salt, phosphate and temperature levels. For example, while TGase increased cohesion, hardness and elasticity when used at 37 °C for 90 min, it did not induce any textural changes when the product was held at 10 °C for 23 h. Finally, the degree of TGase protein cross-linking depends on meat type (Ahhmed et al., 2009). When microbial TGase was used to strengthen chicken or beef meat gels, substantial differences in elasticity were observed. The authors concluded that the elasticity changes may be due physiological differences in muscle and fiber type, substrate variability and presence of transglutaminase inhibitors.

While much research has focused on the use of transglutaminase, there are other cross-linking enzymes that may be able to modify texture of meat and meat products. For example, polyphenol oxidases (PPO) and lipoxygenases can act on sulfhydryl groups and disulfide bonds of proteins. Tyrosinase is a prominent example of a PPO that oxidizes tyrosine residues to quinines. These in turn can then react with sulfhydryl and other amino groups to form tyrosine–tyrosine, tyrosine–cystein or tyrosine–lysine cross-links. To date, there are few studies that investigated their use in other applications than inhibition of browning. Lantto, Plathin, Niemisto, Buchert, and Autio (2006) investigated the effect of addition of tyrosinase and freeze-dried apple pomace powder that contained both TGase and tyrosinase to an industrial pork meat homogenate. They reported an increase of gel strength with the addition of the powder, but little effect of tyrosinase likely to due to the presence of cystein, which is a known tyrosinase inhibitor. Apparently, tyrosinase was not able to form cross-links in myofibillar meat proteins. A more promising approach may be to instead add compounds to meat proteins that tyrosinase is able to cross-link. For example, milk proteins such as β-casein have been shown to be suitable substrates in tyrosinase-induced protein/protein polymerization reactions (Hiller & Lorenzen, 2009; Monogioudi et al., 2009). Similarly laccase, a copper-containing polyphenol oxidase (p-diphenol oxidase) that oxidizes polyphenols, methoxy substituted phenols, and diamines has not yet been investigated for use in meat products. However, with addition of suitable substrates such as fibers or milk proteins to meat products, laccase may become a candidate for texture improvements (Minussi, Pastore, & Duran, 2002). Laccase has been shown to create thermally-stable gels by oxidative cross-linking of sugar beet pectin in the presence of ferulic acid (Littoz & McClements, 2008). With caseinates, gels treated with laccase in the presence of ferulic acid were stronger than untreated controls (Ercili Cura et al., 2009).

3. Advances in meat processing systems

3.1. Introduction

In addition to the above described advances in ingredient systems that may be used to manufacture novel meat products, new processing approaches for the industrial manufacturing of meat products are being developed. This is because the meat manufacturing sector is becoming increasingly more industrialized. In Germany, where per capita consumption of meat products is one of the largest in the world (in 2008, consumers consumed 30.6 kg meat products out of 88.4 kg meat in total, i.e. roughly 35% of all meat consumption was due to meat products such as sausages, hams and others), the number of small scale manufacturers continues to decrease while large-scale industrial manufacturing is growing (Max Rubner Institute, 2008). Table 5 shows the rapid spur in the development of larger meat manufacturing plants. For example, from 2005 to 2007, the total number of industrial meat product manufacturing sites in Germany increased from 931 to 960 (Table 5) while simultaneously, the total number of meat manufacturers, including small (e.g. craft butcher shops), medium and large sized operators decreased (Fig. 1). These shifts from craft style to industrial manufacturing is the result of the massive price pressure that meat manufacturers are facing due to a shift from small individually operated supermarkets to larger discount chains. Similar developments have happened or continue to happen globally. Indeed, in Germany, consumers today are predominantly buying industrially manufactured, low-cost meat products. These industrially manufactured products however must fulfill the highest quality standard, in particular because competition between the discounters is so intense. To ensure consistently high quality while keeping costs down, the meat manufacturing sector is therefore increasing following the example of the dairy sector to replace labor intensive batch processes that may produce products with inconsistent qualities, with continuous processes.

Table 5
Number of German companies producing industrially manufactured meat products sorted by their annual revenue for the period of 2005–2007.

Revenues of industrial meat product manufacturers in Germany (in Mio. €)	Number of companies (in Germany)		
	2005	2006	2007
Under 2	308	288	293
2 − under 5	260	274	278
5 − under 10	129	134	141
10 − under 20	95	104	101
20 − under 50	76	75	80
50 and more	63	65	67
Total	931	940	960

Fully automated, continuous production processes with material deliveries by meat suppliers “just in times” can now be found in the meat manufacturing sector (Nollet & Toldra, 2006). Process and machine specifications are adapted from diverse industries such as the automobile, pharmaceutical, chemical and personal care industries. The goal is to not just to decrease variations in product quality but to also increase throughput. In combination with available expertise in mechanical engineering largely driven by advances in automotive tool design, new machines are emerging that are able to fulfill the above outlined requirements. In the context of this new machinery that is emerging, it is important to note that the previously described novel ingredient systems must now be integrated into these new processing schemes. Enzymes, antioxidants, preservatives, fibers and others may have their functionality differently affected by a high shear continuous grinding systems than by a traditional bowl chopping process. Clearly, there are substantial gaps in the fundamental research base when it comes to the link between novel ingredient systems and continuous meat product manufacturing lines and much work will need to be done the course of the next years to close this gap. Below and as a first step towards this goal we have therefore provided a brief overview over some of the advances in meat processing and manufacturing machineries. Most of these developments have unfortunately not been published in scientific journals. This part of the review is therefore based extensively on recent patent literature and articles published in trade journals.

3.2. Forward feed systems: low and high vacuum fillers

A significant advance in the establishment of continuous meat product production lines has come from the development of equipment that is able to actively transport the material through the production line. In traditional sausage manufacturing, material (meat and fat) is first coarsely cut to provide a standardized meat or fat mass (Nollet & Toldra, 2006). The standardized meat or fat mass is then processed with salt, spices and ice on a bowl chopper where mixing and fine cutting by rotating knives occur simultaneously (Ehrle, Haack, & Kallweit, 2006; Ehrle, Haack, & Kolev, 2001; Ehrle, Haack, & Schnäckel, 2004). Meat batters are removed after the batch process on the bowl chopper has ended, typically when batters are homogeneous and have a desired elasticity. That is the case if proteins have been sufficiently solubilized to form a continuous protein gel network with entrapped water in which fat particles of appropriate sizes are dispersed. The meat batters are then filled into a stuffer, which “pumps” the batter in natural or polymeric sausage casings. This is accomplished by driving a piston forward to reduce the available volume. Sausages are then linked and clipped to be further treated (heated, smoked, fermented etc.). In traditional manufacturing, almost every unit operation occurs in batch.

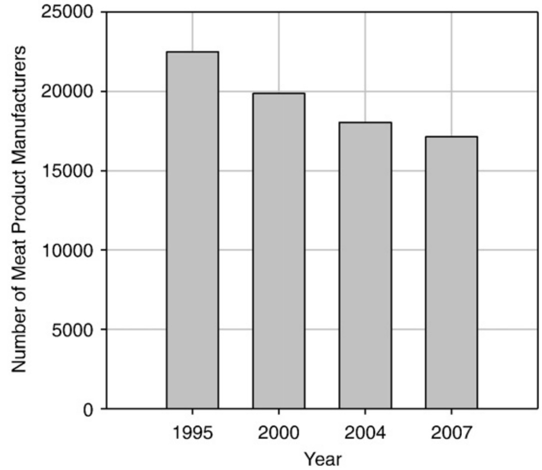

Fig. 1. Total number of meat manufacturing enterprises (small, medium and large) in Germany from the period of 1995 to 2007.

In contrast to this, in modern production lines, material is continuously advanced through grinders, mixers, fine homogenizers, stuffers and clippers. To drive the material forward through the process, vacuum fillers may be used. Vacuum fillers are positive displacement systems that are capable of "pumping" more or less finely ground meat masses. They consist of a combination of a feed hopper, a vane cell feed system and a shutter valve that controls venting and thereby ensures a continuous evacuation (Fig. 2). The first vacuum fillers were sold to the meat industry in the 1950s and were not used in the context of the design of continuous production lines. Rather, they were used as stand-alone stuffers. Today, vacuum fillers are known for their long service life, easy handling and simple changes of programs/products. They may be integrated into a continuous process by connecting them to grinding, portioning, linking, clipping and other devices. A key feature of vacuum fillers is that they generate transport of the material forward without the inclusion of air. This is crucial to ensure that products have less pores, better color and color retention (Wirth, 1998). Moreover, the positive displacement principles ensure a constant flow of sausage batter regardless of changes in material properties. This is in contrast to for example screw feeders, where forward transport occurs by friction between the material and the surface of the screw (Perry & Green, 1997). If friction decreases below a critical point i.e. if materials slip or are too low in viscosity, the material is no longer transported forward. The ability to continuously transport product forward at constant volume flow rates has led to vacuum fillers being used to also fill soups, sauces, delicatessen salads and other foods (Vemag, 2009). Modern servo electric motors ensure that drives operate in silent mode and that much less internal heating occurs (Anonymous, 2007b).

More recently, high vacuum filling machines have been developed. High vacuum fillers are designed much like regular vacuum fillers but have in addition an evacuated feed hopper. They have been used to produce raw fermented sausages such as pepperoni or salami (Handtmann, 2009b,c,d). Custom vacuum filling machines are able to portion materials by shutting the motor that drives the vane cell sequentially on and off. Depending on the size of the hopper and the vane cells, vacuum fillers are able to "pump" extremely coarse meat cuts with the size of a human fist up while maintaining precise portion sizes. With vacuum fillers, there are almost no limitations in terms of size of the to-be-transported meat cuts (Handtmann, 2009a).

One of the key advantages of vacuum fillers is that they can be readily combined with other process equipment. For example, vacuum fillers may be combined with double nozzles to co-extrude the sausage batter with a surrounding casing (Reutter et al., 2003). Fig. 3 depicts the patented design of such a filler–co-extrusion combination. Here, the meat batter is fed through the vacuum filler into an extrusion head system that consists of a double coaxial nozzle system (Bachtle, 2008; Bachtle, Reutter, & Schliesser, 2009). The casing is created by feeding a viscous cross-linkable biopolymer dispersion such as aqueous alginate or collagen gels through the outer slit. The meat batter, which is extruded through the inner opening, is thus "coated" with the biopolymer gel. After exiting the forming zone, the biopolymer gel is converted into a solid by application of a cross-linker, which may be a highly concentrated salt solution or liquid smoke. Alternatively, the nozzle can also rotate to "spin" the casings onto the batter (Risco, 2009). With the combination of forward feed and co-extrusion of a casing, a truly continuous production of sausages is possible.

3.3. Coarse meat grinders and fine meat homogenizer

3.3.1. Coarse meat grinders

Reduction of particle size of meats, the so-called grinding/mincing step, is one of the most widely used process operations in meat product manufacturing. On first sight, the working principle is relatively simple: a pitched screw pushes meat cuts through a grinder system that consists of a combination of a perforated plate with a selected number of holes and specific hole sizes and rotating knives which cut the meat fibers after they have passed through the holes (Rust, 2004). A large variety of different types of grinders can be found on the market including standard grinders, mixing grinders and frozen meat grinders. In combination with specialized separator blades, hazardous parts such as bones, gristle, sinews and other solid particles can be removed from the meat product (Fischer, 1988a,b). However, while the operating principle may be simple, there are a significant amount of variations with respect to available knife–perforated plate combinations. For example, holes may be distributed across the plate in a honey comb like arrangement with holes drilled

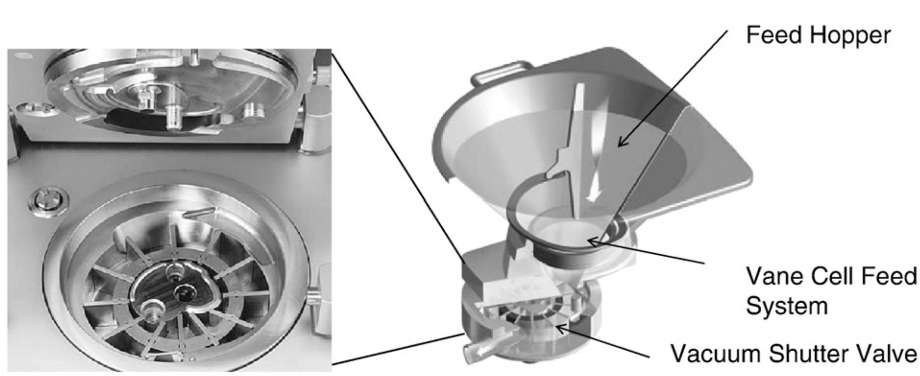

Fig. 2. Schematic and working principle of vacuum fillers. Shown is the Handtmann V612 (Albert Handtmann Maschinenfabrik GmbH & Co. KG, Biberach an der Riss, Germany).

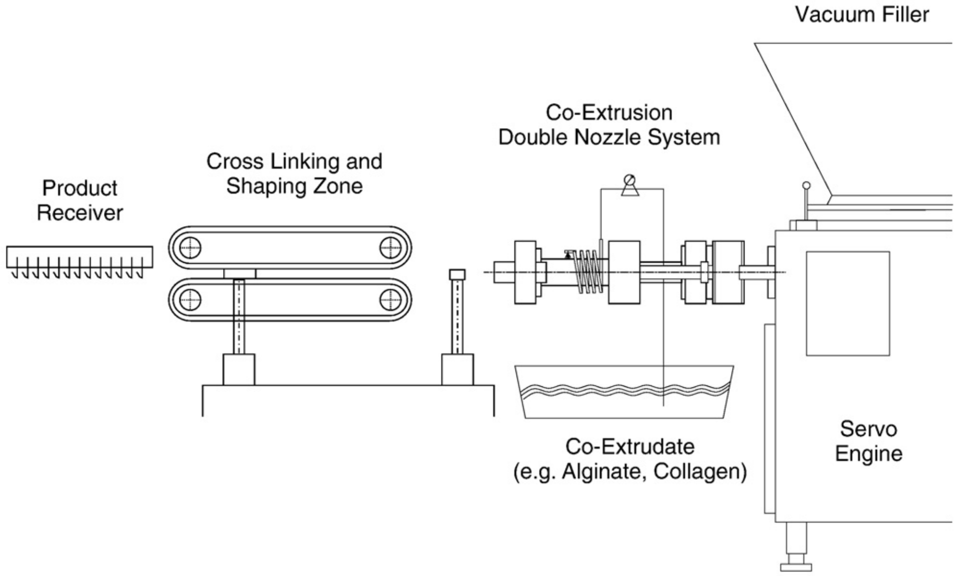

Fig. 3. Schematic of a vacuum filler–co-extrusion systems to continuously produce of sausage batter in natural casing. Shown is the ConPro Albert Handtmann Maschinenfabrik GmbH & Co. KG, Biberach an der Riss, Germany (Reutter et al., 2003).

in a straight through fashion at a 90° angle in relation to the surface of the plate (Syrovatski, 2007a,b). Alternatively, newer perforated plates have holes that are arranged in a multi-start spiral with holes having pitched angles of less than 90° in relation to the plate surface. These design changes have led to increased life times of the tools and more well-defined cuts that improved product quality.

About 15–20 years ago, a small revolution in meat grinding technology took place (Haack, Haack, & Schnäckel, 2003a,b,c,d; Haack & Schnäckel, 2004a,b). The so-called pump grinders, a combination of vacuum filling machine and a connected grinding system, were invented. These rapidly became part of continuous meat processing lines (Haack, 2001a,b,c). In contrast to conventional meat grinders that push the material forward via friction along the pitched screw, vacuum fillers outlined above generate a positive pressure that "pumps" the material through the size reduction zone of the grinder. The pressures that can be generated by the vacuum filler are 4–6 times larger than that of conventional grinders. This has enabled the use of perforated plates with hole diameters as small as 0.25 mm and maintain product flow (Haack & Schnäckel, 2008).

Pump grinders can increasingly produce finer meat batters. Pump grinders can also handle addition of water instead of ice making operating temperatures above 0 °C feasible. This noticeably reduces required cutting forces as materials are viscous rather than a solid. In combination with mixing devices and portioning units one or even two usually required steps in meat processing can be eliminated. Pump grinder may reduce or eliminate issues such as microbial spoilage and oxidative based on the fact that the raw material is relatively mildly treated and air pockets in the meat batter are reduced by the applied vacuum (Honikel, 2004). Theoretically, pump grinders should therefore able to one day completely replace bowl choppers in the production of fine disperse batter (Haack, 2001a,b,c). To date, pump grinders are mostly used for the continuous manufacturing of raw fermented sausages although development of fine dispersing systems is underway (Büchele, 2009). A detailed overview over the characteristics of pump grinders is given in Table 6. Two design examples of knife–perforated plate assemblies are shown in Fig. 4.

One of the few disadvantages of current pump grinders is the problem of abrasion of cutting tools during grinding (Haack, 2007). During operation, plates and knives wear out due to abrasion, which is caused by friction between the raw material and the tool surfaces. In turn, product quality decreases since the material is less efficiently cut. In raw sausages, a smearing of fat can be observed, that is the fat particles no longer exists as well-defined particles in the surrounding protein matrix. Additional coating of plates with abrasion resistant materials has shown to decrease the wear of cutting tools resulting in an improved grinding performance, reductions in temperature increases in the product, and longer service life of the cutting tools.

Table 6
Characteristics of pump grinding systems.

Characteristic	Effect
One step process from ground meat to sausage filled in casings	Continuous material transport between unit operations (grinder, chopper, mixer, and filler)
	Less time consuming, eliminates unnecessary production steps
	Low residence time and small processing zone volumes resulting in narrow residence time distributions and high consistencies in quality
	Less CCPs (critical control points), maximal hygiene
	Lower investment costs for machinery (all-in-one)
	Lower space requirements, less staff needed
Defined particle size in ready-to-fill batter	Ideal for slicers, uniform surfaces of sausage slices
	Low user variability, better standardization
Minimal air content in batter, constant pressure and flow at plates, 100% utilization of plate surface	Excellent color and color stability
	Less mechanical stress
	Low energy consumption
Low temperature increases (<1 °C) in batter	Higher production temperatures for raw fermented sausages feasible (>0 °C)
Optional devices may allow separation of bones, gristle, sinews and other hazardous materials	Less standardization of raw material needed

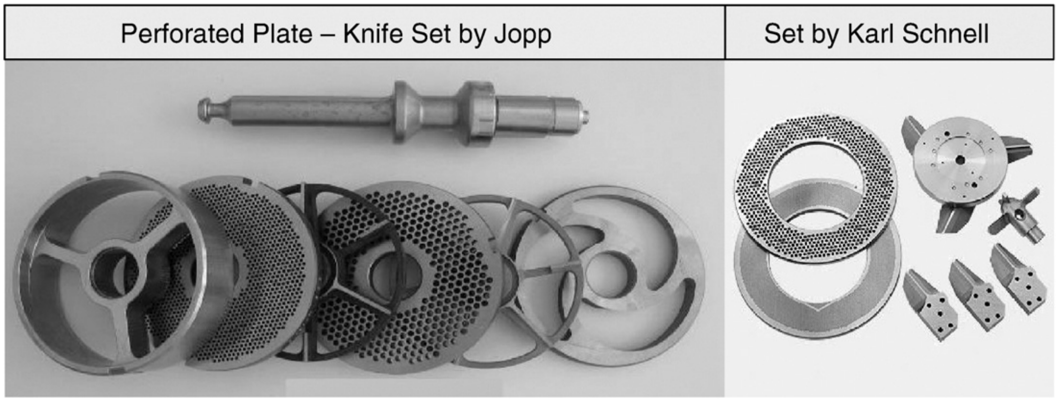

Fig. 4. Two examples of knife–perforated plate assemblies for pump grinders. (Left) 5 piece plate–knife assembly (Turbocut Jopp GmbH, Bad Neustadt, Germany). (Right), Set of cutting tools for plate–knife disperser (Karl Schnell GmbH & Co. KG, Creglingen, Germany).

Haack (2007) reported that after a workload of about 3000 tons of product, no abrasion was observed, the cutting edges of plates and knives were still sharp and plate thickness was not reduced.

3.3.2. Fine meat homogenizers

From the standpoint of traditional processing of emulsion-type sausages of the frankfurter type, bowl choppers are the preferred production equipment. However, as production quantities grow due to consolidation of meat product manufacturers, bowl choppers had to be further and further increased in size. Today, bowl choppers with volumes of 1200 L are available for industrial production of fine sausages (Seydelmann, 2002, 2009). Nevertheless, it appears as if further increases in size are becoming increasingly difficult to implement because of physical restrictions. With larger bowl diameters, the volume of material that is not within an active processing zone (i.e. material that is not in the vicinity of the rotating knifes) is increasing in relation to the amount of material that is actually being processed. To prevent that processing times are increased when bowl sizes are increased, bowl rotational speeds must be increased. This is also required to maintain a narrow residence time distributions. Unfortunately, larger bowl sizes and higher rotational speeds means that stronger motors are required which increases energy expenditures and therefore costs.

Thus, bowl choppers are beginning to be replaced by continuously working fine homogenizers that have design principles similar to those of colloid mills and high shear dispersers used in the broader food industry to manufacture products such as for example mayonnaise. In these systems, residence times are short and "dead volumes", that is volumes where no processing occurs, are low (Inotec, 2009). Residence times can be easily regulated by adjusting volume flow rates. The advantages of such modern meat homogenizers in comparison to bowl are (a) operation in both continuous or batch mode (b) uniform product characteristics such as a narrow distribution of fat particle sizes and consistent gel strengths (c) fully

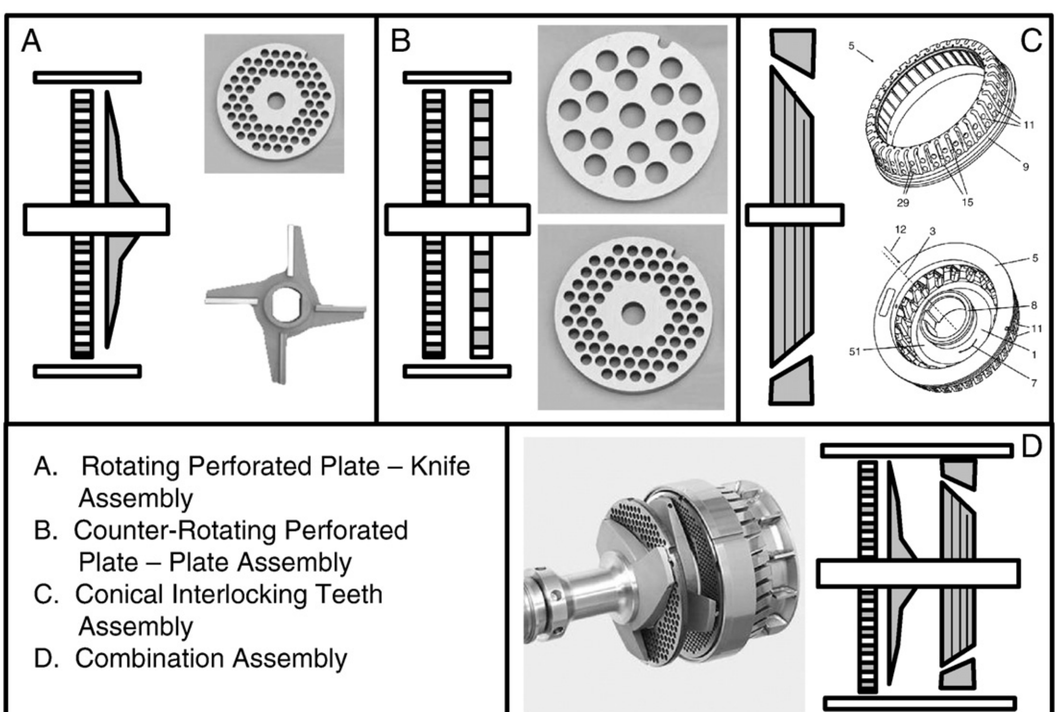

Fig. 5. Principal design of fine disperser for pump grinders. (A) Traditional knife–perforated plate assembly, (B) Counter-rotating plate–plate assembly (C) Rotor–stator assembly (H&S-Mechanische Fertigung GmbH, Wagenfeld, Germany) and (D) Combination of perforated plates with rotor–stator assembly (Karl Schnell GmbH, System "Cutfix", Creglingen, Germany).

Table 7
Advertised advantages of continuously operating meat homogenizers in comparison to bowl choppers.

System	Advantages
All continuous homogenizer	– Excellent temperature control – Small temperature increases – Lower production cost – Shorter processing time – Uniform particle size (fat) – Product qualities independent of operator – From coarse to fine meat batters – Cutting and emulsifying in one step
Plate–knife homogenizer	– Simple maintenance, knife can easily be sharpened – Different combinations of cutting tools possible (3, 5, 7 plates and knives) – Continuous adjustment of cutting tool position during operation – Combinations with other systems possible – Separation blade to remove bones, sinews etc. possible
Fixed or counter-rotating plate/ rotating (cutting) plate	– No metallic abrasion due to the fact that plates are not in contact – Minimal wearing out of cutting tools – Cutting plates have a large number of active cutting zones (edges) – Variable speeds – Low energy costs due to the absence of friction
Stator–rotor homogenizer	– No metallic abrasion, no contact between stator and rotor – No necessity of separating bone and gristle since volume energy input is high enough to disperse them as well – Higher performance (longer service life) than plate–knife system – Minimal wearing out of cutting tools – Low energy costs – 1 or 2 disperser units possible

automated and this only minimally dependent of the operator (d) lower energy costs (e) less air inclusion in sausage batters and therefore less oxidative degradation of products.

Earlier high shear meat homogenizers were simply used as part of the traditional batch process in sausage fabrication. After manufacturing of the batter in a bowl chopper, the batter was passed through homogenizers to stabilize the batter in order to have a more standardized product in the end (Seydelmann, 2002). Today, with a focus on the design of new cutting tools, meat homogenizers are more capable. For example, homogenizers working with rotor–stator tools combine grinding, mixing and homogenization in a single step. With respect to tool design, there are currently three different systems on the market (Fig. 5). The first one is based on conventional meat grinding systems. Rapidly rotating knives and fixed perforated plates with varying hole sizes are used. The knives are driven by a separate drive with motor speeds that can reach as much as 6000 rpm. Product flow rates of 16 tons per hour have been achieved with soft (unfrozen) raw materials (Anonymous, 2004, 2007a). The second tool systems use fixed and rotating plates or counter-rotating plates instead of knives (Seydelmann, 2002, 2009). In this system, there is minimal tool abrasion due to the fact that the plates do not touch. Moreover, due to the larger number of holes in the perforated plates, significantly larger cutting edge surfaces are available to cut meat fibers during the operation. Because of this, plate–knife systems have to be much more frequently re-tooled than counter-rotating plates. No retooling of perforated plates is required until product quantities of 200–1500 tons are reached and tools need only be replaced when approximately 4000–12,000 tons of product has been processed.

Finally, a third tool set is based on a conical shaped rotor–stator system. The product quality is determined by the rotational speed of the rotor and the design of the cutting tool, namely the number and geometry of teeth. Combinations of the above discussed systems are also being developed. For example, a sequentially arranged plate–knife and rotor–stator tool set has been introduced into the market (Fig. 5). All systems allow a fine control of temperature and product flow rates. It should also be noted that meat products containing larger pieces of meat dispersed in a finely ground batter can be manufactured with the help of continuous homogenizers by simply adding a continuous mixer between the homogenizer and the stuffer. Table 7 lists in summary the potential advantages of continuously operating meat homogenizers in comparison to batch operated bowl choppers.

3.4. Slicers

In many supermarkets, the amount of sliced and packaged convenience meat products in the refrigerated section increases while demand for over-the-counter meat products decreases. Consumers prefer the longer shelf life of meat products that is achieved when products are sliced under hygienic conditions followed by vacuum or modified atmosphere packaging (Fankhänel, 2008). Continuous slicer lines are increasingly installed by meat product manufacturers (Holac, 2009). Slicers represent the last in the line of meat production processing steps and are often used in combination with portioning units and/or stacking/shingling devices (Rust, 2004). Balances that control fill weight, tray-feeders, and packaging lines close out the list of advanced machinery used to design continuous production lines (Fankhänel, 2008). The newest generation of slicers is able to ensure precise portioning and high consistency in quality of cuts (Anonymous, 2007a). Volume measurements in combination with weight measurements allow the slice thickness to be regulated depending on product feed. Modern slicer lines are able to cut to accurate weight even if products have irregular shapes as is the case in ham or bacon (Neuhäuser, 1998). High speed slicers can cut 1500 or more slices per minute and ensure a continuous product flow of up to 10 tons per hour depending on slice thickness. Automatic removal of casings and loading of slicer lines has become a standard in large meat manufacturing companies. Today, software is available that allows meat manufacturers to custom design decorative patterns and combine single, shingles and stacks. This is important since the display of sliced products has become a key selling point (Heinrich, 2008). A large assortment of knives suitable to cut products with different textures (e.g. salami or aspic) is available. These newer knives may not require soft product surfaces to be frozen prior to slicing.

4. Conclusions

This review article reviewed advances in the development of ingredient and manufacturing systems for meats and meat products. It highlighted that developments are proceeding at an increasing pace. Driven by the demand for new products with new formulations, the meat industry is forced to install flexible production lines that can generate large quantities of high quality meat products. However, a solid scientific foundation that links newer ingredient systems with modern process operations is somewhat lacking. A review of the literature reveals that new formulation and ingredient systems are often developed without a process in mind and vice versa, processing lines may be developed that are not able to cope with future changes in formulations and ingredient systems. Ultimately, machine designers, process engineers and meat scientists will need to work more closely together to close this gap in the knowledge base. Meat scientists have an important role to play in this process. They are uniquely positioned to bridge the gaps between the different disciplines and thereby help the meat manufacturing sector to prosper.

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